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TECHNICAL REPORT No. 9

SOLID PHASE EQUILIBRIA IN THE Pt-Ga-As AND Pt-Ga-Sb SYSTEMS

by

C.T. Tsai and R. Stanley Williams

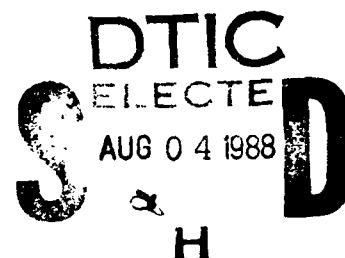
Submitted for Publication

in

Journal of Applied Physics

University of California, Los Angeles
Department of Chemistry and Biochemistry
and Solid State Sciences Center
Los Angeles, CA 90024-1569

July, 1988



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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS N/A	
2a SECURITY CLASSIFICATION AUTHORITY N/A			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited	
2b DECLASSIFICATION/DOWNGRADING SCHEDULE N/A				
4 PERFORMING ORGANIZATION REPORT NUMBER(S) N/A			5 MONITORING ORGANIZATION REPORT NUMBER(S)	
6a NAME OF PERFORMING ORGANIZATION The Regents of the University of California		6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION 1) ONR Pasadena - Administrative 2) ONR Alexandria - Technical	
6c ADDRESS (City, State, and ZIP Code) Office of Contracts & Grants Administration U C L A, 405 Hilgard Avenue Los Angeles, CA 90024			7b ADDRESS (City, State, and ZIP Code) 1) 1030 E. Green Street, Pasadena, CA 91106 2) 800 N. Quincy St., Arlington, VA 22217-5000	
8a NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research		8b OFFICE SYMBOL (If applicable) ONR	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-87-K-0014	
8c ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street, 614A:DHP Arlington, VA 22217-5000			10 SOURCE OF FUNDING NUMBERS	
			PROGRAM ELEMENT NO	PROJECT NO
			TASK NO	WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) UNCLASSIFIED: Tech.Rept.#9 SOLID PHASE EQUILIBRIA IN THE Pt-Ga-As AND Pt-Ga-Sb SYSTEMS				
12 PERSONAL AUTHOR(S) C.T. Tsai and R.S. Williams				
13a TYPE OF REPORT Technical Preprint		13b TIME COVERED FROM Aug '87 TO July '88	14 DATE OF REPORT (Year, Month, Day) 1988 - July - 22	15 PAGE COUNT 18 + Refs & Figs
16 SUPPLEMENTARY NOTATION				
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	ternary phase diagrams - intermetallic compounds - metal/ semiconductor junctions - X-ray diffraction - Solid Phase Equilibria	
19 ABSTRACT (Continue on reverse if necessary and identify by block number)				
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20 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a NAME OF RESPONSIBLE INDIVIDUAL R. Stanley Williams			22b TELEPHONE (Include Area Code) (213) 825-8818	22c OFFICE SYMBOL UCLA

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
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Solid Phase Equilibria in the Pt-Ga-As and Pt-Ga-Sb Systems

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Abstract

Approximate Pt-Ga-As and Pt-Ga-Sb ternary phase diagrams were determined at room temperature with the use of x-ray powder diffraction data. Pt was found to react chemically with both GaAs and GaSb to produce Pt-Ga and Pt/group-V intermetallic compounds. Each semiconductor formed pseudo-binary systems with at least three different intermetallic compounds. The Pt/GaAs interfacial reactions observed by other investigators are discussed and explained in terms of the bulk phase diagram determined in this study.

I. Introduction

The solid state reactions between metal thin films and GaAs have received much attention because of the particular importance of ohmic and Schottky contacts to GaAs devices. A "good" metallization should have a uniform interface between the metal and semiconductor. A reaction between the metal and semiconductor may be necessary for an ohmic contact to ensure good adhesion and a low resistance. On the other hand, a reliable GaAs device utilizing a Schottky barrier should be metallurgically nonreactive, since the barrier height and the contact resistance of the metal/semiconductor junction are sensitive to the structure of the interface. Usually, these systems exhibit complex phase formation and interface morphology. Up to now, the causes of these reactions have not been well understood.

Platinum is a metal with good resistance to chemical attack. However, interdiffusion and chemical reactions involving Pt films on GaAs occur in the relatively low temperature range of 250°-300°C. Annealing at higher temperatures and/or longer time periods produces a layered structure in which PtAs₂ and Pt-Ga compounds such as Pt₃Ga, Pt₅Ga₃, PtGa, and PtGa₂ have been identified.¹⁻¹⁵ Numerous investigations have documented the chemical reactions that occur, but at present there is no framework with which to understand the reaction products or the sequence in which they appear.

Ogawa et al.¹ used x-ray diffraction (XRD), microhardness, and electrical techniques to study annealed Pt/GaAs contacts, and found that the brittle compounds PtGa, PtAs₂, and PtGa₂ formed as the Schottky barrier height decreased. Sinha and Poate^{2,6} investigated Pt/ and W/GaAs Schottky diodes, after annealing at 500°C in vacuum,



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using Rutherford backscattering (RBS) and electrical measurements. They found a layered arrangement of the type PtGa/PtAs₂/GaAs, a decrease of the barrier height and an increase of the ideality parameter for Pt/GaAs but, in contrast, W/GaAs did not exhibit any evidence of reaction. Coleman et al.³ studied this reaction by measuring the movement of the Schottky barrier contact into the GaAs substrate at 300°C to 400°C. They found that the reaction followed a parabolic rate law with an activation energy of 1.6 eV, a gradual increase in the ideality parameter from 1.1 to 1.2, and five distinct layers in the interfacial region.

Murarka^{4,5} used XRD and observed the formation of PtAs₂, Pt₃Ga, and PtGa after the sample was annealed at temperatures in the range from 200°C to 350°C in air, and concluded that oxygen diffusion from the ambient through Pt into GaAs was the cause of the degradation of devices with Pt metallizations. Marcus et al.⁷ examined the premature breakdown sites in Pt/GaAs IMPATT test diodes with Scanning Electron Microscopy (SEM) in Electron-Beam-Induced Current (EBIC) mode with and without annealing in air up to 350°C. They found that premature breakdown occurred primarily at the sites of metallization defects and at the rough edges around the periphery of the diodes. To investigate the Pt/GaAs interface between 250-500°C, Kumar⁸ used reflection XRD, RBS and electrical resistivity measurements, and observed five different Pt-Ga phases and PtAs₂ at various reaction temperatures, with the final products being PtAs₂ and PtGa for a 500Å sample and PtGa₂ for a thinner film (200Å). Cheng et al.⁹ heated 125-9000Å Pt films on GaAs *in vacuo* over the range 250-500°C. Using Auger depth profiling, they found that the reaction initiated with a rapid

migration of Ga into Pt and simultaneous formation of an As-rich layer at the Pt/GaAs interface. Samples heated in air behaved similarly, except for the appearance of a Ga and O surface layer and O at the interface.

Kim et al.¹⁰ investigated this Schottky barrier with Secondary-Ion Mass Spectroscopy (SIMS) and XRD for annealing up to 500°C, and observed a Pt/PtGa₂/PtAs₂/GaAs structure and an irregular change of both the barrier height and the ideality parameter. Feldman and Silverman¹² used ion-induced x-ray analysis to probe the elemental depth profile of a sample heated *in vacuo* for 2 hours at 500°C, and observed a pure Pt-Ga layer near the surface followed by a Pt-As layer of about the same thickness. Begley et al.¹³ investigated samples annealed at 400°C by TEM, Optical Reflection Microscopy, SIMS, XRD, SEM, and energy-dispersive x-ray analysis, and found a complex layered structure at the interface in which Ga had diffused rapidly through the Pt at apparent imperfections in the film. Fontaine et al.¹⁴ studied the interfacial reaction after heating in He for 1/2 to 100h at temperatures from 350 to 500°C by TEM, glancing-incidence XRD, and RBS. They concluded that the reaction had produced PtGa and PtAs₂, the latter of which dominated the contact to GaAs with a strongly preferred orientation on (100) GaAs. Sands, et al. obtained similar results in their RBS and TEM study, and used their data to construct a "thin-film" ternary phase diagram for Pt-Ga-As.¹⁵

The interfacial reactions at the Pt/GaAs interface are similar to those at Au/InP, which have been discussed in terms of the Au-In-P ternary phase diagram.¹⁶ The goal of this study is to map the bulk Pt-Ga-As and Pt-Ga-Sb phase diagrams and use them as the framework for

understanding the chemical reactions described above for Pt/GaAs and for future studies of Pt/GaSb. The next section presents the experimental procedure used in the study. The results of the phase diagram determinations are described and discussed in Sec.III. The Pt/GaAs interfacial reactions are discussed in Sec.IV and the final section contains the conclusions of this work.

II. Experimental Procedure

The experimental procedure was similar to that of the previous study of the Au-III-V systems.¹⁷ The purity of the elements used was better than 99.99%, and the GaAs and GaSb were semiconductor grade. The ampoules in which the samples were heated were made of fused silica. They were cleaned by soaking in aqua regia and rinsing in distilled water. The total sample mass was about 0.5 gram and the estimated error in the atomic composition of the samples was less than one part per thousand. Each sample was placed in an ampoule, which was then evacuated to a vacuum of 10^{-3} Torr and sealed to a volume of about 1 cm³ (diameter and length about 0.5 cm and 5 cm respectively). The sealed ampoules were placed in a resistance furnace and heated to 1150°C for one week to ensure homogenization of the melt. They were then cooled to 25°C at a rate of 5-10K per hour (slower near the melting point of a phase that solidified). The cooling procedures usually required one week, and the resulting samples were solid lumps with perhaps some powder clinging to the walls of the capsule.

The samples were removed from the silica capsules, cut in half and examined with a microscope. Usually, the samples were mixtures of small crystallites of the different phases, although a clear boundary separating phases was evident for some cases. Filings removed from two sides and the center of the samples were investigated with a Phillips X-ray Powder diffractometer, which was interfaced to a microcomputer that controlled the scan rate and collected the data digitally. The diffraction data were collected at 0.1° intervals with a counting time of 10 seconds at each angle. The total time required for a complete scan (2θ from 10°-100°) was 3 hours and the typical signal-to-noise

ratio for a strong diffraction peak was 40 to 1. The composition of each sample was identified by comparing positions, shapes, and relative intensities of the diffraction peaks in the powder patterns of the filings to those of standards prepared for this experiment. The d spacings of the standards were checked against a reference tabulation¹⁸ to ensure that they were identified correctly. At least five diffraction peaks were observed for each of the elements or compounds that were found in the ternary systems. Typical XRD patterns are shown in Fig.1. The identification of a phase from the positions of the diffraction peaks was usually unambiguous, except that both Pt_2Ga and Pt_3Ga had similar crystal structures (bcc) and lattice constants close to that of elemental Pt. The X-ray diffraction pattern of samples prepared for the Pt_3Sb_2 standard were found to be a combination of those of $PtSb$ and Pt_3Sb . For these cases, a careful comparison of the peak shapes and relative intensities was required to identify the phases. A total of 23 different compositions in the two ternary systems were examined, and 16 pseudobinary tie lines were identified. No ternary compounds were found; all the diffraction peaks observed corresponded to either an elemental species or a known binary compound.

III. Phase Diagrams

All of the Pt Compounds with Ga, As, and Sb are listed in Table I, to define the boundaries of the ternary phase diagrams. Guex and Feschotte¹⁹ have studied the Pt-Ga binary system thoroughly and found the formation of eight compounds over limited composition ranges: PtGa_6 (incongruent M.P. 290°C), Pt_3Ga_7 (incongruent M.P. 822°C), PtGa_2 (stable from 153°C to 922°C), Pt_2Ga_3 (incongruent M.P. 937°C), PtGa (M.P. 1104°C), Pt_5Ga_3 (58-63 atomic % Pt, incongruent M.P. 1142°C), Pt_2Ga (incongruent M.P. 1149°C ; two polymorphic transformations at 859°C and 605°C), and Pt_3Ga (67-76 atomic % Pt, M.P. 1374°C). The solubility of Ga in Pt is 14 atomic % at 1361°C and is 6 atomic % at room temperature, while that of Pt in Ga is negligible. The Pt-Sb and Pt-As systems were summarized by Mofatt²⁰ and Shunk.²¹ There are five Pt-Sb binary compounds: PtSb_2 (M.P. 1225°C), PtSb (incongruent M.P. 1043°C), Pt_3Sb_2 (incongruent M.P. 732°C), Pt_3Sb (incongruent M.P. 682°C), and Pt_4Sb (incongruent M.P. 755°C). The solubility of Sb in Pt is about 4 atomic % at 755°C and negligible at room temperature; that of Pt in Sb is negligible. The mutual solubility between Pt and As is negligible and PtAs_2 is the only stable Pt-As compound.

The phases identified, using XRD to analyze the reaction mixtures, for each stoichiometry are given in Table II for the Pt-Ga-As system and Table III for the Pt-Ga-Sb system, and the results of this study are summarized in the ternary diagrams shown in Figs. 2 and 3. Each diagram represents an isothermal cut in the range near 25°C through a three-dimensional plot of the composition of the system as a function of temperature. The phase diagrams are not expected to change much with temperature until the first ternary eutectic melts. All

equilibria are assumed to occur between pure phases, mutual solid solubilities of compounds have been neglected. Hence, the equilibria shown are all pseudobinary and the tie lines of the systems are straight line segments. At higher temperatures, there may be an appreciable solid solubility of one phase in another with the effect of making the tie lines curved or broader. These diagrams were constructed for ideal, closed systems in which no vapor phase is allowed to form, so only condensed phases are present. The Pt-Ga-As phase diagram in Fig.2 is in excellent agreement with the ternary diagram determined by Chang and co-workers at 600°C, at which temperature there are some significant solid solubilities involving two or three compounds.²²

For the Pt-Ga-As system, PtGa_2 -GaAs, Pt_2Ga_3 -GaAs, PtGa - PtAs_2 , Pt_5Ga_3 - PtAs_2 , Pt_2Ga - PtAs_2 , and Pt_3Ga - PtAs_2 were found to be pseudobinary tie-lines. Both PtGa_6 -GaAs and Pt_3Ga_7 -GaAs also have to be pseudobinary from the phase rule. The samples A, B, E, and J (Table II) in the tetragonal region PtGa - Pt_2Ga -GaAs- PtAs_2 were all found to contain four phases. That means the reaction $7\text{PtGa} + 2\text{GaAs} \rightarrow 3\text{Pt}_2\text{Ga}_3 + \text{PtAs}_2$ has a small change of Gibbs free energy ΔG . Because both samples B1 and E have stronger XRD peaks from PtGa than from Pt_2Ga_3 , the PtGa -GaAs cut is assigned to be pseudobinary at room temperature. There was no evidence of elemental As in samples A and J, so apparently GaAs- PtAs_2 is a pseudobinary tie line.

The phase diagram of the Pt-Ga-Sb system is more complex than that of the Pt-Ga-As ternary because there are five Pt-Sb compounds compared to only one Pt-As compound. The cuts PtGa_2 -GaSb, PtSb_2 -GaSb, Pt_2Ga_3 - PtSb_2 , PtGa - PtSb_2 , Pt_5Ga_3 - PtSb_2 , and Pt_5Ga_3 -PtSb are all

pseudobinary tie-lines. In the region of the tetragon bounded by Pt_2Ga_3 - PtGa_2 - GaSb - PtSb_2 , samples A and B (Table III) both contained four different solid phases. Since sample E consisted of PtGa_2 and PtSb_2 and sample A1 displayed stronger XRD peaks from PtGa_2 than those from Pt_2Ga_3 , the PtGa_2 - PtSb_2 is tentatively assumed to be pseudobinary. Sample A2 was quenched at 600°C and showed only PtSb_2 and PtGa_2 . This means that at higher temperatures the PtGa_2 - PtSb_2 system is more favored.

The standard samples prepared for Pt_3Ga , Pt_2Ga , and Pt_5Ga_3 all had similar XRD patterns. Standard samples for Pt_4Sb and Pt_3Sb also had similar XRD patterns, and the pattern of the standard Pt_3Sb_2 sample looked like that of a mixture of Pt_3Sb and PtSb . Also, both Pt_3Ga and Pt_5Ga_3 have a broad stoichiometry range over which they exist. The transition from Pt to Pt_5Ga_3 may be continuous, without a distinct phase change. For the above reasons, it is difficult to map tie lines in the upper region of the Pt_3Ga - Pt_5Ga_3 - PtSb - Pt_4Sb tetragon. However, Pt_5Ga_3 - PtSb , Pt_2Ga - Pt_3Sb_2 , Pt_3Ga - Pt_3Sb_2 , Pt_3Ga - Pt_3Sb , and Pt_3Ga - Pt_4Sb were tentatively assigned as tie lines after careful comparison of the XRD patterns of samples and standards.

IV. Discussion

Because Pt-GaAs is not a pseudobinary tie line in Pt-Ga-As, Pt is unstable with respect to GaAs in a closed system, and will react to form products. The stoichiometry of a GaAs sample with a deposited Pt film, schematically represented by an X in Fig.2, is on a line connecting Pt and GaAs, which will intersect four tie lines: $\text{Pt}_3\text{Ga-PtAs}_2$, $\text{Pt}_2\text{Ga-PtAs}_2$, $\text{Pt}_5\text{Ga}_3\text{-PtAs}_2$, and PtGa-PtAs_2 . The solubility of Ga in Pt is 6% in the temperature range from 25°C to 600°C. At room temperature, the Pt/GaAs interfacial reaction is limited by diffusion. When the temperature is high enough, Ga diffuses into the Pt film to form the Pt(Ga) solid solution. This diffusion of Ga into Pt was found to obey a parabolic rate law.³

As Ga atoms substitute into the Pt lattice, the cell constant of the Pt should change. This gradual change in the lattice parameter of the deposited Pt film was observed by Sinha and Poate,² and Kumar⁸ from XRD patterns. On the other hand, it is difficult for As atoms to diffuse into the Pt film, because the solubility of As in Pt is negligible.²⁰ The As atoms will stay at the interface and combine with Pt to form PtAs_2 . This is consistent with observations from RBS,⁶ Auger depth profiling,^{2,9} X-ray fluorescence spectroscopy,⁸ and SIMS¹¹ experiments, which all showed As remaining close to the metal/semiconductor interface. This PtAs_2 phase was seen at the earliest stage, even before PtGa appeared,⁸ and was present through the final stage of this interfacial reaction in most of the studies. The increase in the electric resistivity⁸ may be caused by the solution of Ga in Pt, by the formation of PtAs_2 at the interface, or both.

As more Ga diffuses into the Pt film, the local atomic ratio of Ga will exceed the limit of solubility of Ga in Pt, and the Pt_3Ga phase will be produced. Pt_3Ga has a face-centered cubic structure like that of Pt, but the lattice parameter is a little smaller than that of Pt, 3.892Å vs 3.921Å, which means that the x-ray diffraction peaks occur at slightly larger angles. The Pt_2Ga phase, which has an atomic structure similar to that of Pt_3Ga and nearly the same lattice constant, 3.892Å vs 3.889Å, should form after Pt_3Ga . As can be seen from Fig.2, the Pt_3Ga phase exists over a broad range of homogeneity from 24 to 33 atomic percent Ga, with the 33 percent composition being very close to the 33.3 percent Ga composition of Pt_2Ga . During the reaction, the continuous increase of the Ga concentration and continuous decrease of the lattice constant of Pt_3Ga make it difficult to identify the formation of Pt_2Ga from XRD patterns. This may be the reason that Pt_2Ga has not been reported in thin-film reactions.

The next Pt-Ga intermetallic phase, Pt_5Ga_3 , was found by Kumar⁸ in a series of experiments with Pt films thicker than 2000Å. This phase has not been reported in other studies in which the films were thinner, perhaps because at this stage the reaction proceeds rapidly. It is possible that the Pt_5Ga_3 phase was also masked by the Pt_3Ga phase in XRD patterns. The reaction continues until the compound PtGa is formed, which is connected to GaAs by a tie line in Fig.2. Thus, PtGa and GaAs can coexist in equilibrium in a closed system. This stage was recognized by several researchers^{4,8,14,15} as "reaction completed" with PtGa and PtAs_2 being the final Pt-containing products.

The initial reaction is rapid and follows the parabolic rate law³ (diffusion-controlled). It is found that films thicker than

1000Å require a much longer time to react "completely" than an extrapolation from lower film thicknesses would indicate, and this is described as being due to extremely slow diffusion of Ga through the interfacial PtAs_2 that forms⁸ (interface-controlled). It is also found that Ga migrates continuously out of the GaAs and through the PtAs_2 at a very slow but finite rate. For a diffusion-controlled reaction, the reaction rate depends on the diffusion rate, $J = -D \cdot dC/dx$, in which D is the diffusion coefficient and dC/dx is the concentration gradient. In the beginning of the reaction, the concentration gradient is very large, so the reaction is fast. As gallium diffuses into the Pt film, however, the local concentration gradient of Ga will decrease quickly and cause the reaction rate to slow down. The sharp reduction of the rate of the interfacial reaction may be due to the decrease of the Ga concentration gradient, as much as to a barrier formed by the PtAs_2 at the interface.

The activation energy of this interfacial reaction was determined by Coleman³ and Kumar⁸ to be 1.6eV and 2.3eV, respectively. The 1.6eV value was determined by measuring the temperature dependence of the movement of the metal/semiconductor interface into the GaAs at 300-400°C. The 2.3eV activation energy was obtained by measuring the temperature dependence of the time for the reaction to complete in the same temperature range as in the previous investigation. However, since the rate is not constant during the reaction, the time to completion is not a suitable measure of the rate of reaction. Kumar also obtained an alternate value of 1.43eV from the time to reach the maximum XRD peak shift of Pt. These values are smaller than those for the thermal decomposition of pure GaAs, 3.9eV by Lou and Somorjai,²³

but larger than those for the evolution of gas-phase As species from Au/GaAs, 0.43eV by Mojzes.²⁴

In the ideal case, a thick Pt film deposited on a GaAs substrate, if annealed slowly, might be expected to form a diffusion couple with separate layers of Pt/Pt(Ga)/Pt₃Ga/Pt₂Ga/Pt₅Ga₃/PtAs₂/GaAs. Each layer would be in local equilibrium at the interface with its neighbors. For a thin Pt film, there may be only one Pt-Ga intermetallic phase coexisting with PtAs₂ and the GaAs substrate, depending on the thickness of the Pt film and the reaction kinetics. In a closed system, the final equilibrium products of a Pt/GaAs reaction should be PtGa and PtAs₂, because there is a pseudobinary tie line connecting PtGa with GaAs.

The phase diagram may be used to predict the composition of the equilibrium Pt/GaAs contact to be PtGa, PtAs₂, and GaAs, because its composition is within the tie triangle PtGa-PtAs₂-GaAs. These are the phases that most investigators report in thin-film studies. However, annealing in an open system such as *in vacuo*, or under a pressure of inert gas, may cause both PtAs₂ and GaAs to decompose thermally to produce gas-phase As species. In that case, the stoichiometry of this system would move to the Ga-rich side in the phase diagram and Pt₂Ga₃, which also coexists with PtGa and GaAs, can be produced. With the loss of further As, other Pt-Ga intermetallic compounds, such as PtGa₂⁸ and Pt₃Ga₇, may be produced. The most stable Pt-containing condensed phase in contact with GaAs should be PtGa₆, which would presumably be formed after annealing for long times and high temperatures in an open system.

V. Conclusion

The ternary condensed phase diagrams for Pt-Ga-As and Pt-Ga-Sb near room temperature have been determined. Platinum is not a thermodynamically stable contact metal with respect to either of the semiconductors GaAs or GaSb. However, at least three Pt-Ga compounds are found that are thermodynamically stable with respect to each of these two semiconductors in closed systems. After annealing, both Pt-Ga compounds and PtAs₂ or Pt-Sb compounds are expected to be produced at the Pt/GaAs and Pt/GaSb interfaces. Experimentally, the Pt-Ga compounds are found in the outer layers and PtAs₂ is formed near the GaAs interface. The Pt/GaAs interfacial reaction appears to be a diffusion-controlled process.

Acknowledgments

This work was supported by the Office of Naval Research, the University of California MICRO program, and Hughes Aircraft Corporations. RSW further thanks the Camille and Henry Dreyfus Foundation and the Alfred P. Sloan Foundation for additional support.

Table I. Binary phases in Pt-Ga, Pt-As, and Pt-Sb binary systems

<u>Phase</u>	<u>Pt atomic %</u>	<u>Melting Point</u>
Pt (Ga)	94	1769-1361°C
Pt ₃ Ga	67-76	1374-1149°C
Pt ₂ Ga	66.6	1149°C
Pt ₅ Ga ₃	58-63	1142-1017°C
PtGa	50	1104°C
Pt ₂ Ga ₃	40	937°C
PtGa ₂	33.3	922°C
Pt ₃ Ga ₇	30	822°C
PtGa ₆	16.7	290°C
PtAs ₂	33.3	>800°C
Pt ₄ Sb	80	755°C
Pt ₃ Sb	75	682°C
Pt ₃ Sb ₂	60	732°C
PtSb	50	1043°C
PtSb ₂	33.3	1225°C

Table II. Composition of Ternary Mixtures : Pt-Ga-As

<u>Sample</u>	<u>Stoichiometry</u>				<u>Phases</u>
	Pt	Ga	As		
A	1	1	1		GaAs, PtAs ₂ , Pt ₂ Ga ₃ , PtGa(m)
B1	1	2	1		GaAs, PtGa(m), Pt ₂ Ga ₃ (m), PtAs ₂ (w)
B2	1	2	1	600°C	GaAs, Pt ₂ Ga ₃ (m), PtAs ₂ (w), PtGa(w)
C	1	3	1		PtGa ₂ , GaAs
D	4	7	1		Pt ₂ Ga ₃ , GaAs
E	7	9	2		GaAs, PtGa, Pt ₂ Ga ₃ , PtAs ₂ (w)
F	3	2	2		PtGa, PtAs ₂
G	11	3	1		PtAs ₂ , Pt ₅ Ga ₃
H	6	1	6		PtAs ₂ , Pt ₃ Ga
I	3	1	2		PtAs ₂ , Pt ₂ Ga
J	7	6	6		PtAs ₂ , PtGa(m), Pt ₂ Ga ₃ (m), GaAs(m)

Table III. Composition of Ternary Mixtures : Pt-Ga-Sb

Sample	Stoichiometry			Phases
	Pt	Ga	Sb	
A1	1	1	1	PtSb ₂ , GaSb, PtGa ₂ , Pt ₂ Ga ₃ (w)
A2	1	1	1	600°C PtSb ₂ , PtGa ₂
B	1	2	1	GaSb, PtGa ₂ , PtSb ₂ (m), Pt ₂ Ga ₃ (w)
C	1	3	1	GaSb, PtGa ₂
D	1	1	3	PtSb ₂ , GaSb
E	4	7	1	PtGa ₂ , PtSb ₂
F	7	6	6	PtSb ₂ , Pt ₂ Ga ₃
G	4	3	2	PtSb ₂ , PtGa
H	7	3	4	PtSb ₂ , Pt ₅ Ga ₃
I	9	3	4	PtSb, Pt ₅ Ga ₃
J	8	3	2	PtSb, Pt ₂ Ga (or Pt ₅ Ga ₃)
K	21	9	2	Pt ₂ Ga, Pt ₃ Sb ₂
L	12	3	2	Pt ₃ Ga, Pt ₃ Sb ₂
M	6	1	1	Pt ₃ Ga, Pt ₃ Sb

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Figure Captions

FIG.1 X-ray powder diffraction patterns of (a) sample F and (b) sample B1 in the Pt-Ga-As system, and (c) sample C and (d) sample E in the Pt-Ga-Sb system.

FIG.2 Solidus portion of the Pt-Ga-As ternary phase diagrams at 25°C. The three Pt-Ga phases with a range of stoichiometries are represented by broad lines. The dashed line indicates the "best guess" for an uncertain tie-line.

FIG.3 Solidus portion of the Pt-Ga-Sb ternary phase diagram at 25°C. The range of stoichiometries of the Pt-Ga phases are not shown because of the complexity of this system. The dashed lines indicate the "best guess" for uncertain tie-lines.

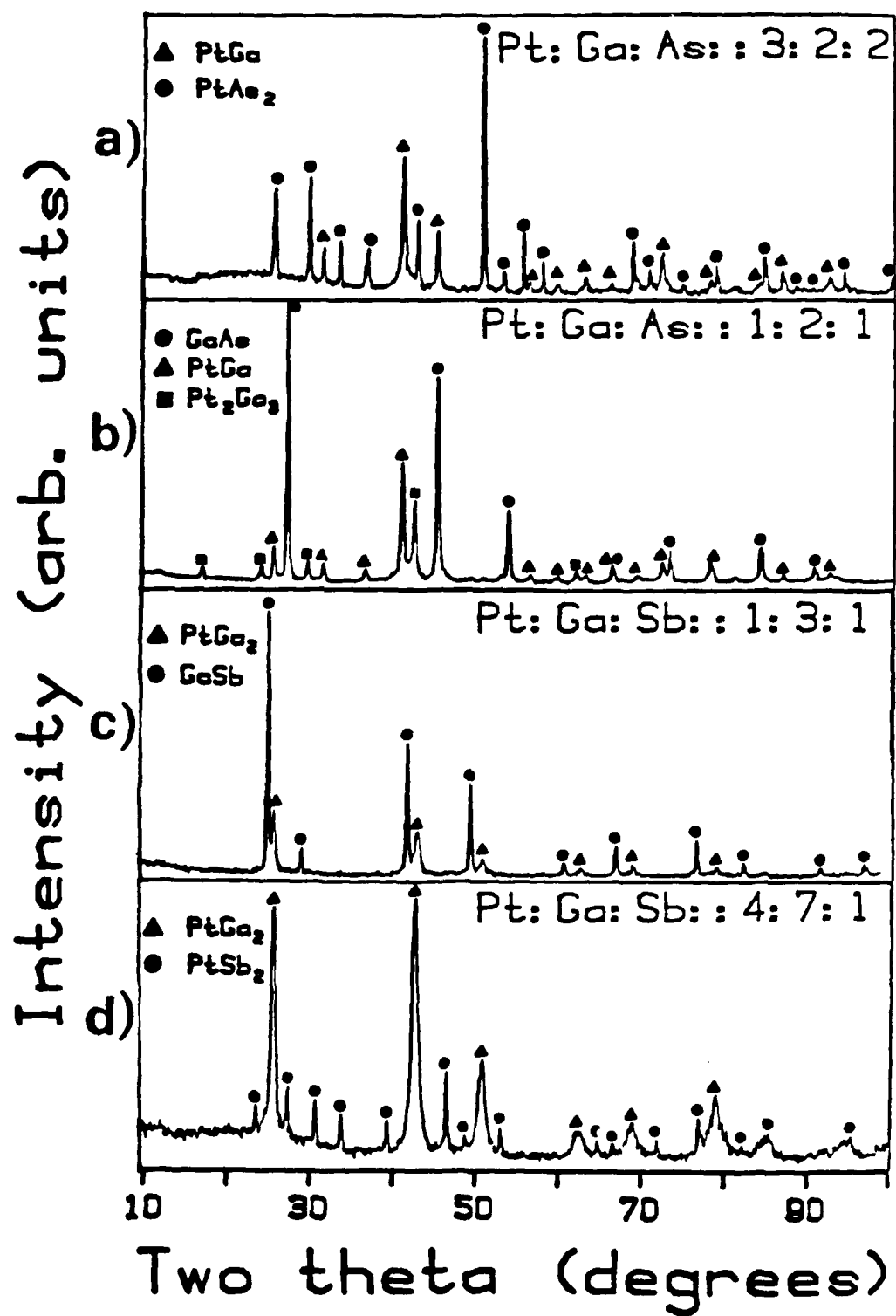


FIG.1

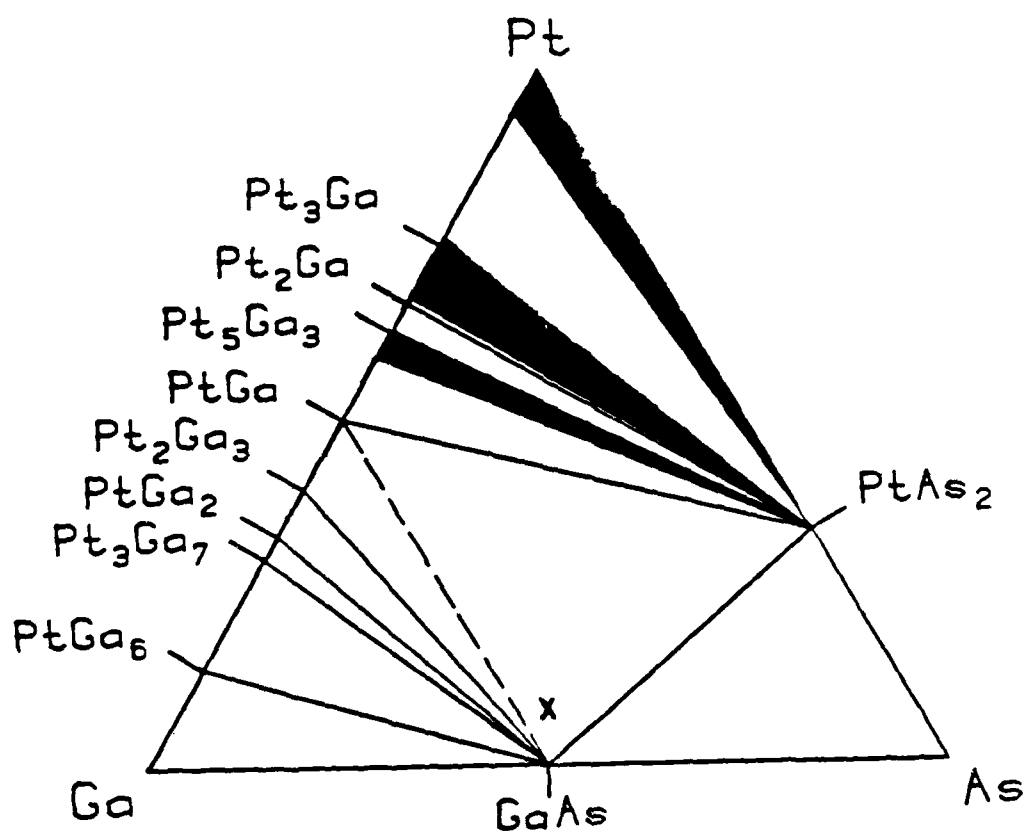


FIG. 2

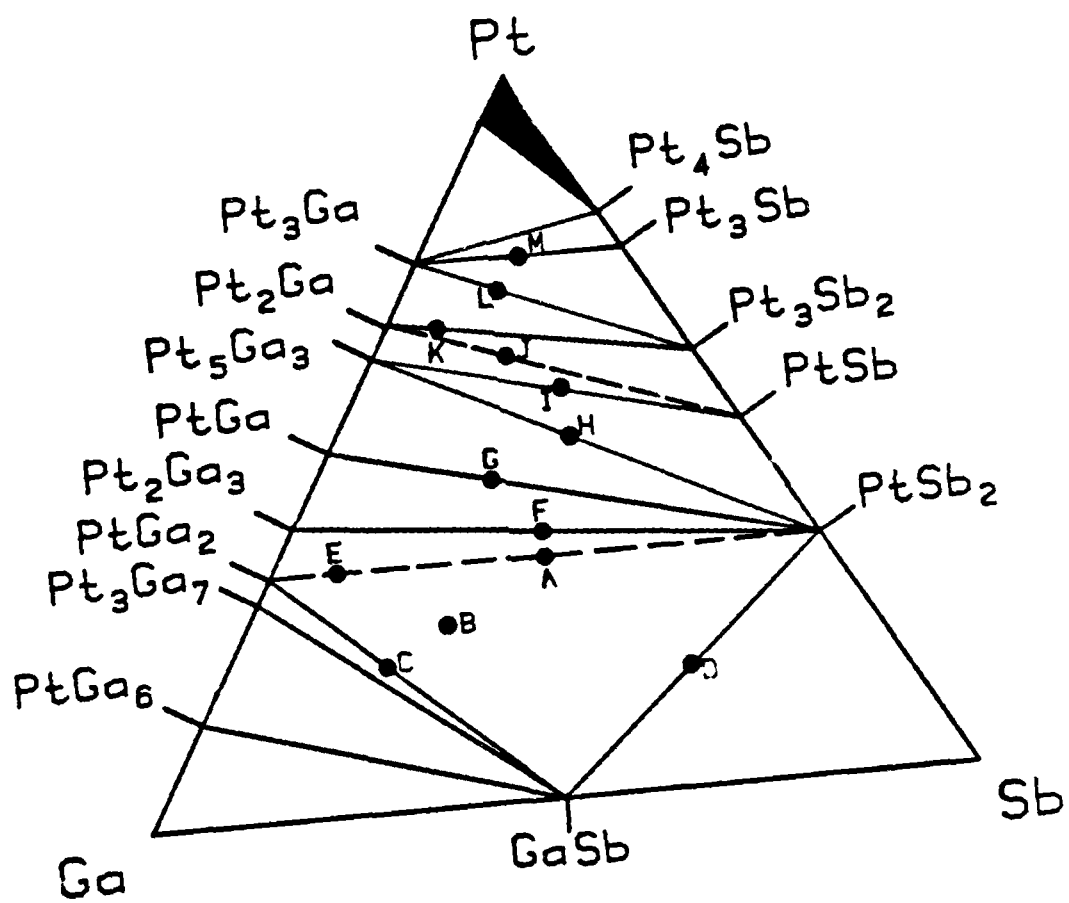


FIG.3

DAT
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